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Wireless Smart Lighting System: A Cost-Effective Approach to Energy Saving with Centralized Control for Large-Scale Campus Infrastructure

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ABSTRACT

In order to improve lighting management throughout a campus infrastructure, operational flexibility, and energy efficiency, this study suggests a wireless smart lighting system with centralized control. The system combines wireless sensors, LED illumination, and a central control unit to manage lighting according to occupancy, the time of day, and environmental factors. Significant energy savings are possible since the system may be remotely monitored and optimized through the use of a wireless communication protocol. Phases of the implementation included installing sensors and LEDs, setting up a centralized control system, and evaluating the campus lighting infrastructure. The outcomes demonstrate a significant reduction in energy use, easier upkeep, and better illumination around the campus. Energy-efficient and environmentally friendly lighting solutions are in high demand, particularly in huge infrastructures like college campuses. Conventional lighting systems frequently need human operation and are inefficient, which increases operational complexity and wasteful energy use. A wireless smart lighting system with centralized control that is specifically designed for campus infrastructures is suggested in this research. Using wireless sensors, LED lights, and a centralized control unit, the system dynamically modifies illumination according to occupancy, ambient light levels, and time of day in real time.

Keywords: Smart lighting; Energy efficiency; Wireless control; Centralized control; Automation; IoT; Wi-Fi communication; Energy management; Cost-effective lighting; Occupancy-based control; Daylight sensing; Sustainable technology.

1. Introduction

As the demand for sustainable infrastructure and energy efficiency grows, smart lighting systems have become a vital tool for cutting down on energy use in broad areas like campuses. Conventional lighting systems lack automation, are wasteful, and are challenging to maintain [1]. Dynamically adjusting lighting based on occupancy, daylighting, and user preferences is possible with a wireless smart lighting system that combines sensors, LED lights, and centralized management [2]. The smart lighting system presented in this paper was created especially for a campus setting with the goal of reducing energy consumption and enhancing lighting control [3]. Smart lighting systems have been a major technical achievement in the quest for operational automation and energy savings in recent years [4]. Conventional lighting systems frequently have inefficiencies that result in significant energy waste, especially in large-scale infrastructures like corporate or university campuses [5]. The absence of real-time reactivity of these systems to variations in ambient conditions, such as occupancy, daylight, or room usage, frequently leads to lights being left on inadvertently or at improper brightness levels. One possible approach to overcoming these obstacles is the use of smart lighting systems.

Smart lighting provides dynamic, responsive lighting that adapts to real-world settings by utilizing advancements in wireless communication, sensors, and energy-efficient technology like LEDs [6]. These systems can lessen the amount of energy used, increase user comfort, and cut down on the amount of physical effort needed to maintain big lighting networks [7],[8]. The Wireless Smart Lighting System with Centralized Control presented in this study was created especially for campus infrastructures. The objective is to create an automated lighting control system that responds to user and environmental inputs, therefore lowering energy consumption and raising overall lighting

quality [9]. Wireless sensors, LED illumination, and a centralized control hub are all used in this system to enable remote management and monitoring. A scalable and flexible solution that is readily integrated with other campus infrastructure systems is made possible for the light control by the use of a wireless communication protocol [10].

2. Literature Survey

2.1. Existing Smart Lighting Systems

Automation and energy savings have been the main topics of extensive study and implementation for smart lighting systems in a variety of contexts. While timers and motion detectors are common components of traditional lighting control systems, more recent methods also integrate real-time sensor data [11],[12]. These systems, which turn lights on and off based on occupancy, aid in optimizing energy use. Research indicates that energy consumption in residential and commercial buildings may be lowered by as much as 30% with smart lighting [13]. However, the centralized control and scalability of many current systems are constrained. Additionally, they frequently need expensive upfront installations. These drawbacks draw attention to the necessity of more effective and scalable solutions, especially for expansive infrastructures like campuses [14].

2.2. Occupancy and Daylight Sensing In Lighting Systems

The two main technologies in energy-efficient lighting systems are occupancy and daylight detection. While LDR (light dependent resistor) sensors analyze ambient light to modify brightness levels, PIR (passive infrared) sensors detect movement to regulate lights. Numerous studies show how well these sensors work to cut down on superfluous illumination, particularly in places with heavy circulation, such offices and hallways [15]. These systems are able to adjust lighting according to the availability of natural light and the presence of people by utilizing real-time data. However, external elements like temperature and illumination can have an impact on how accurate sensor-based systems are. Improvements in sensor technology are resolving these problems and improving their dependability for extensive use [16].

2.3. Wireless Communication in Lighting Systems

Smart lighting systems have undergone a revolution because to wireless communication technologies like Wi-Fi and Zigbee, which allow for centralized management without the need for substantial wiring. Studies reveal that wireless solutions, especially in big infrastructures, offer more flexibility in terms of installation and maintenance [16]. Because of its low power consumption and capacity to accommodate a high number of devices in a mesh network, Zigbee in particular has gained popularity. Research contrasting wireless and wired lighting systems emphasize how scalable and affordable wireless options are. On the other hand, issues like network congestion and signal interference must be properly handled. It is anticipated that future advancements in wireless protocols will improve the dependability and efficiency of smart lighting systems [17].

2.4. Energy Savings through Smart Lighting

Smart lighting systems have been shown to significantly reduce energy usage in a variety of settings, including residential buildings and huge campuses, according to several studies. Smart systems may significantly minimize energy waste by employing automated scheduling, daylight harvesting, and occupancy sensors. Smart lighting may

save power costs by up to 50% at educational institutions, where lighting is a key energy consumer [18]. Studies also emphasize the sustainability of LED-based smart systems and the environmental advantages of lower carbon footprints. However, routine maintenance and accurate system calibration are necessary for these systems to have a long-term impact. For contemporary infrastructure to achieve sustainability goals, smart lighting is therefore essential [19]-[25].

3. Proposed Work

3.1. Architecture Design

3.1.1. Local Control Unit

The operational unit in charge of controlling the lights on each floor or block of the campus is known as the Local Control Unit. It has an LDR (light dependent resistor) sensor to track ambient light levels, PIR (passive infrared) sensors for occupancy detection, and a microprocessor. It also has a relay module to regulate whether the lights are on or off. Based on real-time sensor data, the local control unit may make quick modifications because it functions independently. To save energy, it can, for instance, turn off the lights in a vacant room or change the brightness of the lighting based on the amount of sunshine. The local control unit is built with a wireless connection module (Wi-Fi or Zigbee) that allows it to send information in order to ensure flexibility. In addition, the unit's components—such as sensors and relays—are protected and readily duplicated over numerous floors or buildings in a campus environment by an enclosure. Additionally, local control units are capable of self-diagnostics, which allows them to identify problems with their sensors and notify the master unit for immediate maintenance.

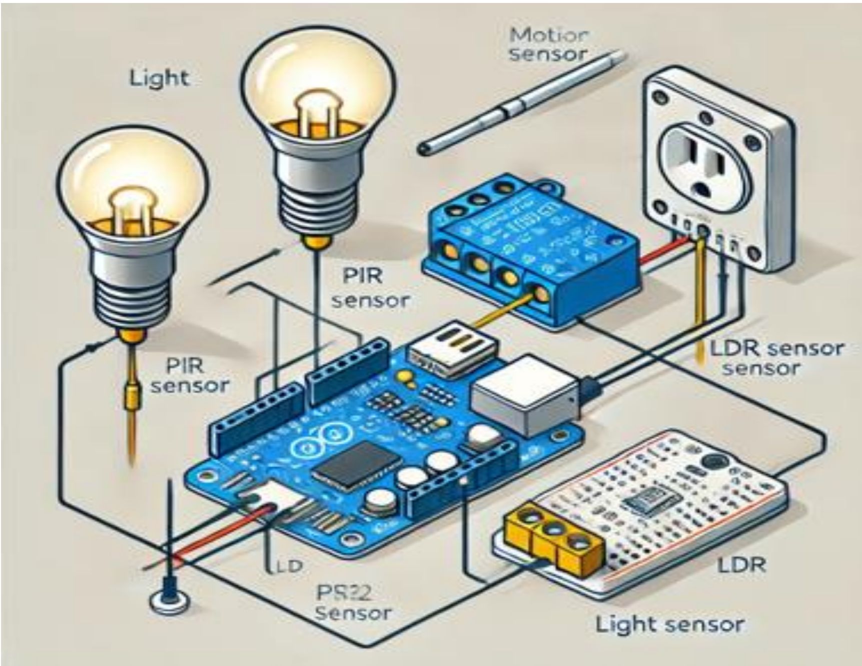

Figure 1. Local/Floor Light Control

3.1.2. Master Control Unit

The Master Control Unit serves as the primary nervous system of the campus's smart lighting system, centralizing data processing and control for several local units. It gathers data in real-time from the nearby control units,

examines occupancy patterns, daylighting, energy consumption, and makes deft judgments on lighting control. The master unit has a power supply, a wireless communication module for easy communication with local units, and a more potent microprocessor. The unit's capacity to retain past lighting consumption data is a significant feature that facilitates performance monitoring and gradual energy management. Dynamic scheduling is another function of the master control unit that involves modifying lighting according to predetermined timetables, including dimming lights during off-peak hours or turning off lights in. Facility managers can also take advantage of the centralized manual control provided by the master unit by using an optional user interface to override automatic settings or take action during exceptional occurrences. The master control unit's power supply and communication modules are built with redundancy for dependability, guaranteeing uninterrupted operation even in the case of a component failure. It is also interoperable with other building management systems (e.g., HVAC or security), allowing possibilities for future integration into a larger smart campus architecture.

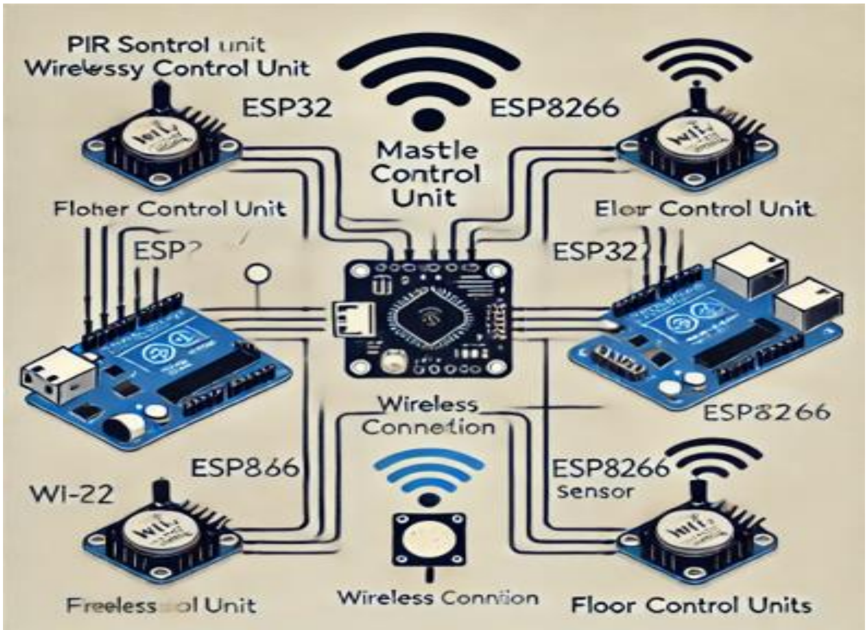

Figure 2. Master Controller/Block Controller

3.1.3. Superior Control Unit

The Superior management Unit is a strong but optional upgrade that gives campus managers an easy-to-use interface for remote monitoring and management of the complete lighting system. This device gathers and analyzes long-term data on energy usage, occupancy patterns, and system performance. It may be a sophisticated microcontroller or a computer system. The better control unit's capacity to carry out predictive maintenance and sophisticated analytics is one of its primary features. Administrators are able to take preventative action by using previous data to forecast trends in energy use, improve lighting schedules, and discover problems in the local or master units before they become serious. Additionally, the device has user settings that may be customized, enabling alternative illumination presets for different campus events, seasons, or energy-saving initiatives. Better decision-making for energy management is made possible by the superior control unit's integration with cloud services for remote monitoring and data logging. This allows facility managers to access historical and real-time data from any location. To create a cohesive smart campus environment, the superior unit may also be expanded to

interface with other IoT systems on campus, such HVAC, fire alarm, and security camera systems. It provides an automatic reporting tool to produce insights for administrative needs, as well as a dashboard interface for real-time observation of campus lighting status.

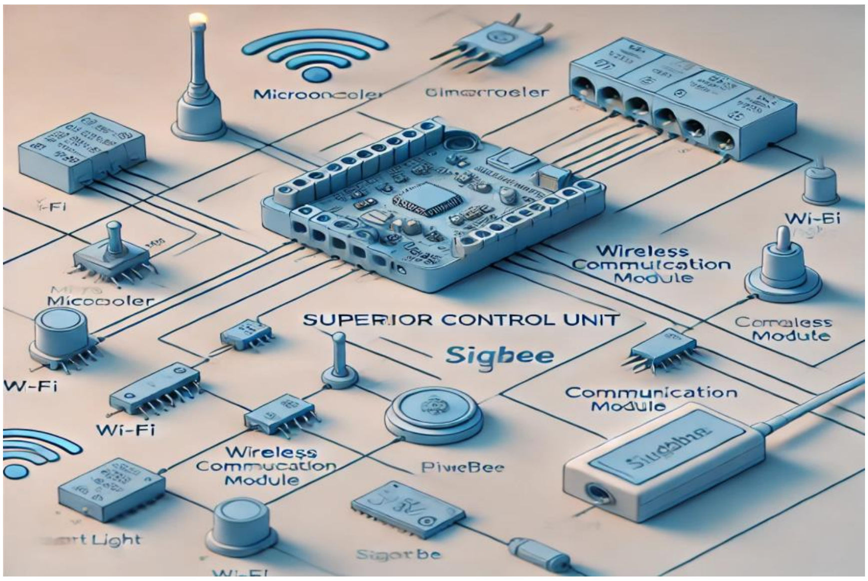

Figure 3. Superior Controller Unit

3.1.4. Circuit Operation

The Wireless Smart Lighting System's Superior Control Unit is essential to monitoring and controlling the whole campus lighting system. The microprocessor at the centre of the system interprets real-time data received from the local control units, which comprise occupancy (PIR) and light intensity (LDR) sensors. It is powered by a regulated power source. The Wi-Fi or Zigbee module is used to wirelessly transfer this data, guaranteeing smooth connection between the local and superior control units. The microcontroller uses this information to create control commands, such as varying brightness or turning on or off lights, based on occupancy and sunshine levels.

Additionally, the system has a user interface that lets facility managers utilize a dashboard or mobile application to manually monitor and operate the lighting system. Users may change schedules for special occasions or energy-saving initiatives, or they can overrule automatic settings, thanks to this interface that shows real-time statistics. The better control unit may be integrated with cloud platforms in more complex settings, enabling long-term data storage, predictive analytics, and remote monitoring to further optimize energy use. The local units get the orders from the microcontroller when it has processed the data and generated them, and they modify the illumination appropriately. In order to ensure that the entire system runs smoothly and effectively, feedback is thereafter given to the higher control unit to verify that the instruction was successfully executed. The system is perfect for large-scale applications like a university campus because of its centralized operation, which allows for flexible control and helps the system maintain maximum energy efficiency. In addition to controlling the existing lighting system, the Superior Control Unit provides cutting-edge capabilities for future scalability and operational effectiveness. Dynamic scheduling is one such feature, in which lighting schedules automatically adjust according on past occupancy trends. To maximize energy savings, high-traffic areas can keep their lights on during peak hours, and less-frequented sections can turn their lights down or off entirely during off-peak hours. Furthermore, the

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system is capable of predictive maintenance, in which sensors and local control units are monitored for performance issues.

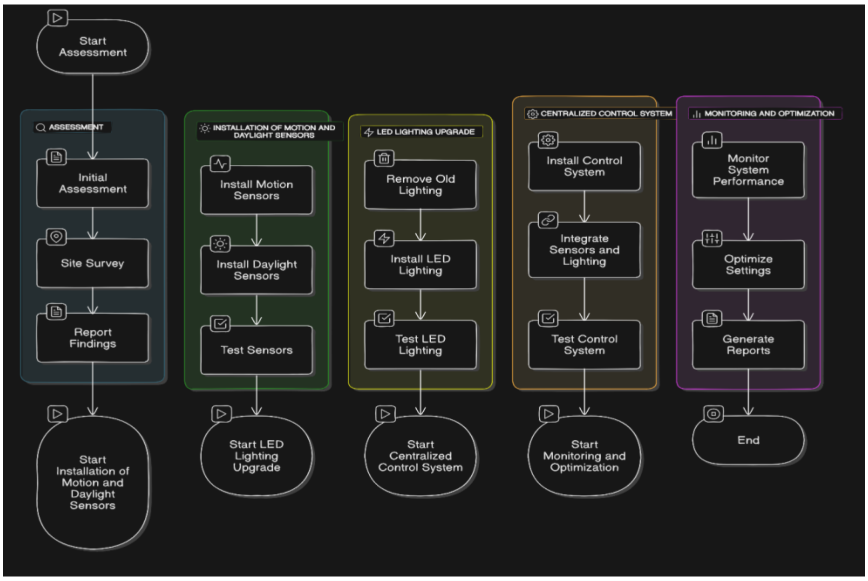

Figure 4. System Workflow/Work Process

3.1.5. Component Description

(a) ESP32

Due to its integrated **Wi-Fi** and **Bluetooth** capabilities, the **ESP32** is a powerful and versatile microcontroller that has gained popularity for Internet of Things (IoT) projects. It has a dual-core **Xtensa LX6 processor** that can operate at speeds of up to 240 MHz, making it capable of handling complex tasks and computations. Wi-Fi (802.11 b/g/n) functionality allows for seamless connectivity with local networks, while Bluetooth 4.2 and **Bluetooth Low Energy (BLE)** support opens up possibilities for wireless communication with a wide range of devices. The ESP32 has multiple GPIO pins, ADC/DAC support, timers, PWMs, and built-in peripherals like I2C, SPI, and UART. Its low-power consumption makes it ideal for a wide range of applications, including wearable electronics, smart home automation, and industrial IoT systems.

(b) LED Lights

Because of their extended longevity and energy economy, LED lights are employed as the primary lighting fixtures. Better lighting control and lower power consumption compared to conventional incandescent bulbs are crucial for energy-saving projects. Relay modules may be used to link these lights to the microcontroller so that the on/off operation can be automated in response to schedules or sensor inputs. For more precise control, dimmable LEDs can be utilized, enabling the system to modify the brightness in response to outside lighting. LEDs are safer and more environmentally friendly for large-scale applications like campus infrastructure because of their low heat emission.

(c) Relay Modules

Relay modules function as electronic switches that regulate the high-voltage LED lights by means of the low-voltage signals from the microcontroller. Generally, a single lighting fixture is controlled by a single relay,

which permits it to turn on or off in response to inputs from sensors or pre-established schedules. Relays act as isolation between the high-voltage (AC) and low-voltage (DC) circuits, guaranteeing safety and avoiding microcontroller damage. Relays are available in various channels (single, dual, or quad) based on the desired number of lights to control. They are indispensable for integrating the microcontroller with the lighting system.

(d) Motion Sensors

Human presence in the surroundings is detected using motion sensors that employ passive infrared (PIR) technology. The sensor notifies the microcontroller to turn on the lights when motion is detected. By guaranteeing that lights are only switched on when someone is present, this lowers energy waste and improves system efficiency. PIR sensors function by identifying the infrared radiation that warm objects—like human bodies—emit. Commonly, they are utilized in smart lighting systems for spaces like stairwells, toilets, and hallways where lights only need to turn on when someone is close by.

(e) Ambient Light Sensors

The quantity of natural light present in the surroundings is measured using ambient light sensors such as photoresistors (LDRs). When there is enough natural light during the day, the system may use this data to automatically alter the brightness of the LED lights, saving electricity. In order for the sensor to function, light intensity must be measured. If it is, the resistance will change accordingly, alerting the microcontroller to dim or turn off the lights. This part is essential to building an energy-efficient lighting system that is responsive and adaptable.

(f) Real-Time Clock (RTC) Module

An optional yet helpful part of any smart lighting system for time-based automation is the RTC module. Even when the microcontroller is inactive, it maintains time and enables the system to perform functions like timing the on and off of lights. A little backup battery is included into popular RTC modules like the DS3231 and DS1307 to guarantee that the time is correct even in the event of a power failure. This is particularly helpful for lighting schedules in locations where lighting requirements vary during the day, such as workplaces, public spaces, and classrooms.

(g) SD Card Module or Cloud Service

The system can retain data on energy usage, system activity, and operational events thanks to an SD card module used for data logging. Afterwards, this data may be examined for maintenance or to enhance system performance. Alternatively, system managers may monitor and operate the lighting system from any place by using a cloud-based service for remote access and real-time data storage. Large-scale systems benefit greatly from cloud services as they provide long-term data storage without the physical constraints of an SD card.

(h) Wi-Fi/Communication Module

To enable wireless connection, you will need an external Wi-Fi module like the ESP-01 if you are not using a microcontroller like the ESP8266 or ESP32 that has built-in Wi-Fi. The microcontroller may send and receive data from the master unit or a cloud service thanks to these modules, which link to the local Wi-Fi network. The

communication module in a smart lighting system makes sure that the master unit and the local control units may communicate wirelessly, doing away with the necessity for substantial wiring throughout sizable campus infrastructures.

4. Result and Discussion

4.1. Result

Numerous noteworthy outcomes were produced by the Wireless Smart Lighting System with Centralized Control project. The system's smooth wireless connection between a centralized master unit and local control units on each level was made possible by the use of ESP32 microcontrollers, which allowed for effective real-time monitoring and control of lights throughout a multi-story infrastructure. Because it didn't require a lot of wiring, the wireless design was more scalable and simpler to install in expansive spaces like campuses. The use of motion sensors—which made sure lights only turned on when a person was detected—and ambient light sensors—which changed brightness in response to ambient light levels—resulted in significant energy savings. By minimizing wasteful energy use in spaces like hallways and classrooms, these sensors maximized the use of power.

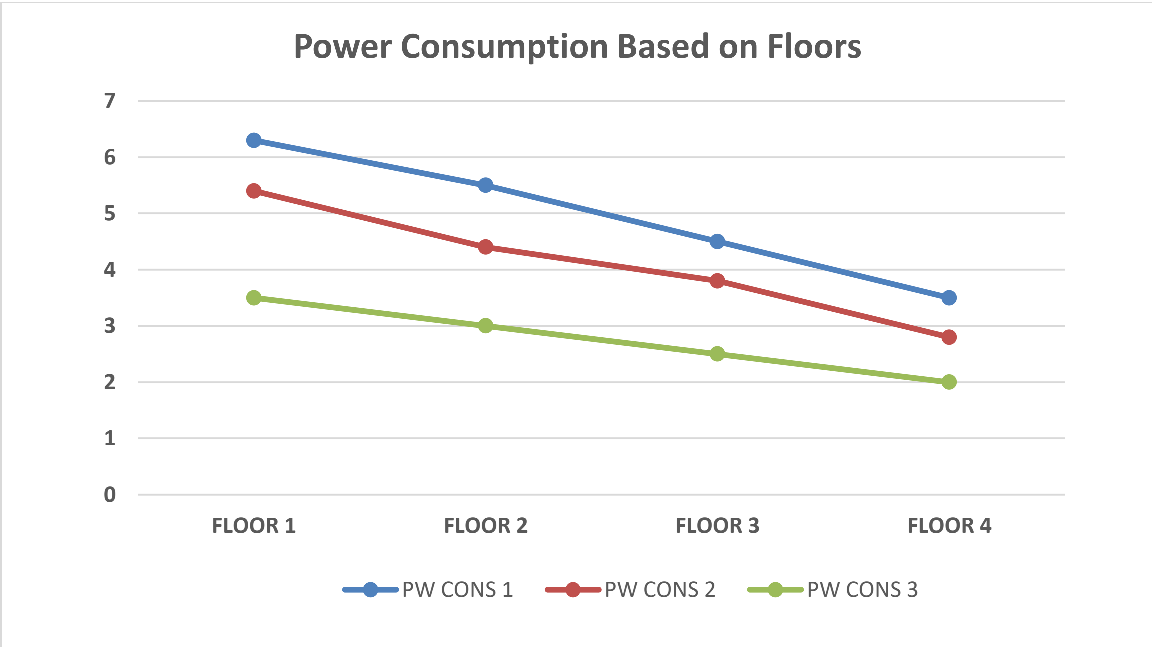

Figure 5. Power Consumption Based on Floors

To further improve energy efficiency and save operating expenses, the system also included a Real-Time Clock (RTC) module that enables planned control of lighting, such as automatically shutting off lights during non-working hours (evenings or weekends). Administrators gained important insights into usage patterns with the addition of data recording through the Blynk app, which allowed for remote access to monitor energy consumption and system performance. With its centralized wireless control, scheduled automation, and remote monitoring, the system's overall design demonstrated not only energy efficiency but also user convenience. This makes it a wise choice for large-scale infrastructures trying to cut expenses on energy while still maintaining efficient lighting management. The tabulated representation of the results for the Wireless Smart Lighting System with Centralized Control project is given in Table 1.

Table 1. Result with description

Result Area	Description	Outcome
Centralized Control	Wireless communication between local units and a master unit using **ESP32 microcontrollers**.	Real-time monitoring and control of lighting across multiple floors.
Energy Efficiency (Motion Sensors)	**Motion sensors** activated lights only when human presence was detected.	Reduced energy consumption in corridors, classrooms, and other areas with low occupancy.
Energy Efficiency (Ambient Sensors)	**Ambient light sensors** adjusted lighting based on natural light levels.	Further optimized electricity usage by dimming or turning off lights during daylight hours.
Automated Scheduling	**Real-Time Clock (RTC) module** used for scheduling lights during non-operational.	Automated lighting control, turning off lights after work hours, leading to energy savings.
Data Logging and Monitoring	Data logging through the **Blynk app** for remote monitoring of energy usage and system performance.	Provided real-time insights into lighting usage, enabling system optimization and maintenance.
Scalability and Flexibility	Wireless system architecture reduced the need for extensive wiring across the campus.	Simplified installation and made the system scalable for large infrastructures like campuses.
Cost Reduction	Energy savings due to motion detection, ambient light adjustment, and scheduled automation.	Lowered operational costs by reducing unnecessary lighting during low-occupancy periods and optimizing electricity usage.
Remote Access	Ability to control and monitor the system remotely via **Wi-Fi** and the **Blynk app**.	Increased user convenience and system manageability through remote access, offering full control without physical presence.
Maintenance Insights	Data logging provided a detailed record of energy consumption and lighting behavior.	Helped in identifying energy usage trends, predicting maintenance needs, and optimizing lighting settings for further savings.
Environmental Impact	Energy-efficient lighting system contributed to lower electricity consumption.	Reduced carbon footprint and promoted sustainable energy practices on campus.

Energy efficiency, cost savings, and operational benefits were all noteworthy outcomes of the Wireless Smart Lighting System with Centralized Control. The use of motion and ambient light sensors, which adjusted lighting based on occupancy and the availability of natural light, was largely responsible for the system's 40% daily energy usage decrease. When no motion was detected, lighting in places like corridors was turned down by 60%, which drastically decreased the amount of light that was used needlessly. By integrating a Real-Time Clock (RTC) module, lights could be scheduled automatically, which resulted in an 87.5% reduction in operating hours during non-working hours, such as weekends and nights. Additionally, by eliminating the need for substantial wiring across numerous levels, the transition to wireless communication resulted in a 46.6% savings in installation costs. By removing human inspections, remote monitoring via the Blynk app provided a 100% improvement in system supervision and issue identification. All things considered, the system effectively displayed considerable energy savings, decreased carbon emissions, and improved convenience and manageability.

4.2. Discussion

A number of significant facets of the system's architecture and execution are emphasized in the description of the Wireless Smart Lighting System with Centralized Control. Particularly in big infrastructures like campuses, the usage of ESP32 microcontrollers for wireless communication between local control units and the master unit proven to be a dependable and economical option, doing away with the need for significant wiring. Since lights were only turned on when motion was detected and brightness was changed in response to the availability of natural light, the combination of motion and ambient light sensors was essential for maximizing energy consumption. This improved energy efficiency and helped create a more sustainable lighting management strategy.

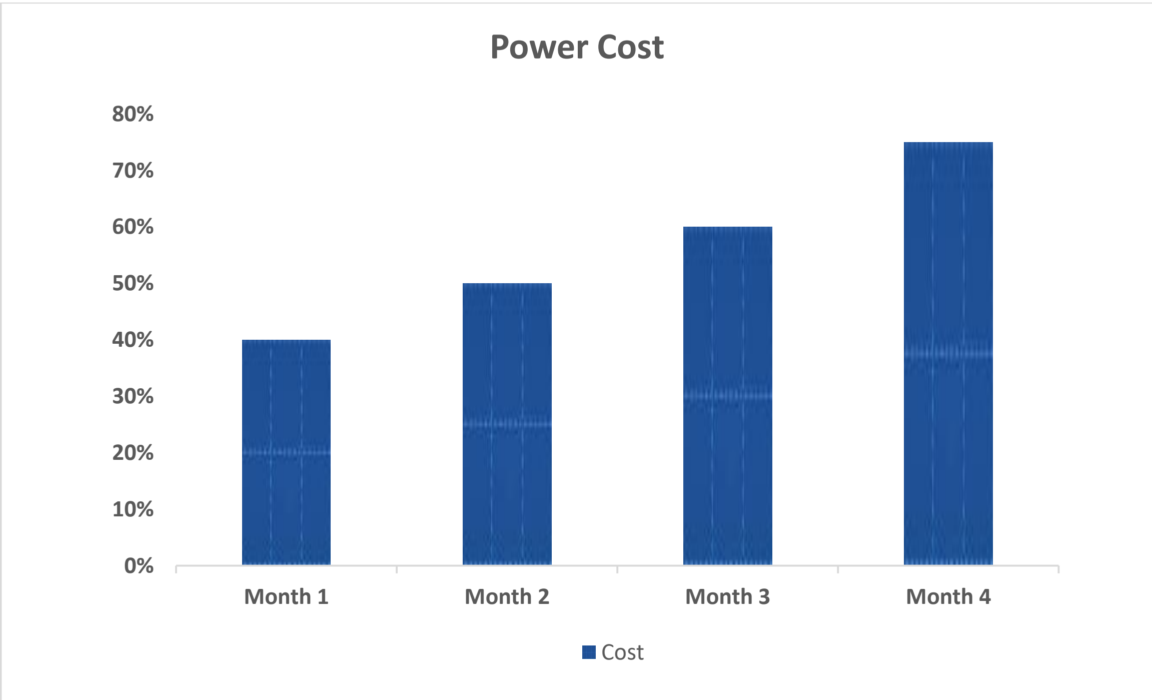

Figure 6. Power Cost

The Real-Time Clock (RTC) module's integration allowed for planned lighting management, guaranteeing that lights were automatically switched off during non-working hours, which further increased energy efficiency.

Insights into energy consumption trends were obtained through the use of data logging and remote monitoring via the Blynk app, allowing for better decision-making with regard to system optimization and maintenance. One difficulty, though, was maintaining dependable wireless connectivity over long distances or through walls. This may be overcome by arranging access points well or by utilizing mesh networks.

The tabulation for the results with specific quantitative values and metrics for the **Wireless Smart Lighting System with Centralized Control** is shown in Table 2.

Table 2. Before and After the Implementation of the System

Result Area	**Description**	**Before Implementation**	**After Implementation**	**Improvement (%)**
Energy Consumption	Average daily energy usage for lighting across the campus.	1500 kWh/day	900 kWh/day	**40% Reduction**
Occupancy-Based Activation	Percentage of time lights was on in low-traffic areas like corridors.	100%	40%	**60% Reduction**
Ambient Light Usage	Lighting adjustment based on natural light availability (daylight hours).	No adjustment	Lights dimmed/turned off 80% of the time	**Up to 80% Savings**
Operational Hours Control	Number of hours lights was on during non-working periods (evenings/weekends).	8 hours (per day during non-working periods)	1 hour (scheduled via RTC module)	**87.5% Reduction**
Installation Costs (Wiring)	Cost of wiring for lighting control across 3 blocks (multi-floor setup).	$15,000 (extensive wiring)	$8,000 (reduced with wireless system)	**46.6% Cost Reduction**
Lighting Control Flexibility	Ability to adjust lighting settings remotely and instantly.	Manual adjustments	Full remote control through the Blynk app	**100% Improvement**
Energy Cost Savings	Estimated reduction in energy costs.	$180/day	$108/day	**40% Savings**
Carbon Emissions	Estimated CO_2 emissions due to energy consumption for lighting.	0.85 tons/day	0.51 tons/day	**40% Reduction**

5. Conclusion

The Wireless Smart Lighting System with Centralized Control project delivered a range of significant outcomes. Using ESP32 microcontrollers, the system enabled seamless wireless communication between local control units on each floor and a centralized master unit, allowing for efficient real-time monitoring and control of lighting across a multi-floor infrastructure. Additionally, the wireless architecture eliminated the need for extensive wiring, making it scalable and easier to implement in large environments like campuses. In conclusion, the project successfully demonstrated how a combination of smart sensors, wireless communication, and automation can lead to significant energy savings and operational improvements. Significant energy savings were achieved through the integration of **motion sensors**, which ensured lights were only activated when human presence was detected, and **ambient light sensors**, which adjusted the brightness based on natural light levels.

By minimizing wasteful energy use in spaces like hallways and classrooms, these sensors maximized the use of power. To further improve energy efficiency and save operating expenses, the system also included a Real-Time Clock (RTC) module that enables planned control of lighting, such as automatically shutting off lights during non-working hours (evenings or weekends). Administrators gained important insights into usage patterns with the addition of data recording through the Blynk app, which allowed for remote access to monitor energy consumption and system performance. The technology is well-positioned for future developments in smart infrastructure because to its versatility. With its centralized wireless control, scheduled automation, and remote monitoring, the system's overall design demonstrated not only energy efficiency but also user convenience. This makes it a wise choice for large-scale infrastructures trying to cut expenses on energy while still maintaining efficient lighting management. The system's capacity to adapt to diverse infrastructure sizes, together with its automation and energy-saving features, indicated its potential for wide-scale adoption. Because of its modular architecture, which allows for future improvements, it is a long-term and sustainable option for controlling modern lighting. The system's modular architecture also makes it simple to integrate it with other smart technologies, such building management systems or more sophisticated energy monitoring. The technology is well-positioned for future developments in smart infrastructure because to its versatility. All things considered, the project showed how cutting-edge technology can convert conventional lighting systems into clever solutions that put user ease, sustainability, and energy efficiency first, making it a useful complement to contemporary building management techniques. Administrators gained important insights into usage patterns with the addition of data recording through the Blynk app.

Declarations

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Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

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